Active Optics for a Segmented Primary Mirror on a Deep-Space Optical Receiver Antenna (DSORA)

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This article investigates the active optical control of segments in the primary mirror to correct for wavefront errors in the Deep-Space Optical Receiver Antenna (DSORA). Although an exact assessment of improvement in signal blur radius cannot be made until a more detailed preliminary structural design is completed, analytical tools are identified for a time when such designs become available. A brief survey of appropriate sensing approaches is given. Since the choice of control algorithm and architecture depends on the particular sensing system used, typical control systems, estimated complexities, and the type of equipment required are discussed. Once specific sensor and actuator systems are chosen, the overall control system can be optimized using methods identified in the literature.

I. Introduction

Laser communication from deep-space probes to Earth requires a receiver telescope efficient at maximizing the signal energy incident on a photodetector and minimizing stray background light so that the system can achieve the highest data rates [1]. Although a receiving telescope does not require high-resolution imaging optics for communication, blurring of the signal spot in the focal plane forces the pupil in the telescope to expand so that sufficient signal strength can be detected. The increased pupil size also permits a higher flux of stray light due to blue-sky scattering and astronomical background sources. Blurring of the signal spot can be caused by mirror-surface roughness, panel misalignment, mirror-figure error due to gravitational sag, wind load and thermal expansion, mechanical vibrations in the mirror and support structure, or atmospheric perturbations.

The remainder of this article briefly surveys some causes of blurring. Recommended correction techniques are given in Section II. Applicable sensing approaches are reviewed in Section III, followed by a discussion of control approaches in Section IV. Concluding remarks are given in Section V.

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II. Causes of Blurring

One of the causes of focal-plane blur is the roughness of the telescope's primary mirror segments. This is one of the static contributions of the overall blur radius. Although roughness is largely avoidable by using high-quality optical surfaces, large-area mirrors with $\lambda/10$-rms roughness are extremely difficult to build and, therefore, are very expensive. A compromise solution is a mirror of medium roughness, in the $\lambda/2$–2λ range. Since distortion of wavefronts by mirror-surface roughness does not change, active optical correction is not required. A static correction can be made with a phase-compensating filter in a pupil plane corresponding to a demagnified image of the primary mirror aperture once the wavefront error due to surface roughness has been determined.

Blurring due to mechanical vibrations in the support structure or mirror surface can be minimized with improved structural design and active optics compensation. Since bandwidths of mechanical disturbances are often in the kilohertz range, active optics must have fairly high bandwidth control and sensing systems to compensate for these disturbances. A recent task management report on Precision Segmented Reflectors (PSR)[2] showed that figure errors due to mechanical disturbances on the Moderately Focused Mission were predicted to be less than 1 μm rms in an uncompensated reflector. Active optical compensation was recommended for reduction of the rms error below this value. Because of the high bandwidth requirements for active correction of vibrational wavefront errors, passive structural isolation and damping are probably more appropriate than active compensation for a receiver telescope, since high-quality imaging is unnecessary.

Atmospheric distortions also tend to have bandwidths in the kilohertz range. These can only be corrected by active optical compensation. It has been shown that the use of an actively controlled segmented mirror can give much improved seeing in the presence of atmospheric distortions [2,3,4]. However, the expense of a high-bandwidth-control mechanism probably renders atmospheric correction inappropriate for a receiver telescope. In addition to the expense of implementation, the improvement provided by the correction of atmospheric distortions would probably be limited by the roughness of the primary mirror.

Figure distortions tend to have very low bandwidth. These distortions are caused by thermal expansion effects and force loading, such as gravity and wind. Since these are often subhertz bandwidth disturbances, a low-frequency active-optics-compensation system is feasible if sensing and control of mirror segments can be done at reasonable expense. The amount of wavefront distortion due to thermal expansion and force loading depends largely on the particular structural design and materials; therefore, the benefit of quasi-static active segment control cannot be predicted until a well-defined preliminary design is available. Once such a design exists, software analysis can determine both thermal effects [5] and force-loading effects [6]. Estimates of blurring for corrected and uncorrected systems can be compared at that time.

III. Sensing Approaches

There are several approaches for sensing wavefront errors due to atmospheric fluctuations and figure distortions [2,7].[3] Some approaches use the front surface of the primary mirror and others use the back side. Front-surface-sensing (FSS) systems have the advantage of using light that actually passes through the optics of the telescope rather than relying on correct figure modeling from measured back-side positions of the segments. In addition, unlike back-side-sensing systems, some FSS systems can sense atmospheric errors. The FSS systems that use interferometric techniques are probably inappropriate for the DSORA system because of the large amount of surface roughness allowed for the primary mirror of this system. Incoherent FSS systems usually image calibrated stars to sense wavefront distortions and, therefore, require interruption of signal reception during sensing. Back-surface-sensing (BSS) systems can be operated concurrently with signal reception. A comparison of front- and back-surface-sensing approaches has been made.[4]

The BSS system[5] senses the edges between mirror segments by using interferometry, as shown in Fig. 1. Two interference sensors are located on each side of the boundaries between mirror segments. Local tilt of each segment is measured by the comparison of the adjacent sensor signals at a given edge. Piston position is calculated by a global assessment of the local tilt data. The system requires a stable reference plane at each detected edge location and considerable software to match the local edge offset and tilt measurements to get a global figure estimate. The BSS system has the advantage of operating

[2] D. H. Lehman, "Precision Segmented Reflectors (PSR) Monthly Report," Jet Propulsion Laboratory and NASA Langley Research Center (internal document), Jet Propulsion Laboratory, Pasadena, California, June 1990.

[3] *Precision Segmented Reflector Figure Control System Concept Definition Report*, JPL D-5895 (internal document), Jet Propulsion Laboratory, Pasadena, California, October 1988.

[4] Ibid.

[5] Ibid.

without disrupting the signal flow to the photodetector, so that continuous correction is possible.

Two FSS approaches use incoherent light from calibrated stars as references. One approach is the Hartmann technique [2], in which the aperture of the telescope is subdivided and each subaperture is displaced and imaged, as shown in Fig. 2. The overall wavefront shape is estimated by a computerized model that joins together the tilts measured in each subaperture. The location of the center of each subimage in the system describes the direction and magnitude of the tilt for the subaperture. This system can be costly, because an array of deflecting optics is required as well as a detector array for each subaperture imaging point. Furthermore, it is unlikely that the sensing subapertures could be divided in the hexagonal pattern of the primary mirror segments unless a segmented prism is used. Since the detection is performed in the image plane, perhaps an electromechanically deployed optics shelf containing the Hartmann deflection optics could be used. This sensing requires a calibrated object, so a table of known stars and their characteristics must be maintained.

Roddier proposes a system that measures the irradiance at pupil planes equispaced in front of and behind the image plane, as shown in Fig. 3 [7]. This system is designed for use with a (continuous) deformable membrane mirror, and although Downie and Goodman suggest that the system is insensitive for segmented mirrors [10], an averaging algorithm could be developed to optimize the tilt and piston correction of each segment. Software would have to detect the output of the sensor system in regions corresponding to mirror segments and calculate the piston and tilt adjustment for each segment. This process differs significantly from the nearly direct control proposed by Roddier for the membrane mirror and eliminates much of the elegance of that sensing system's excellent compatibility with the control variables.

Further complications may develop as a result of the boundaries between the mirror segments in Roddier's system because it was designed for a continuous mirror surface. The gaps between segments may invalidate the geometric approximations for a segmented mirror used in [7]. If the detector pixel size is significantly larger than the demagnified gap width, this problem should be negligible. An additional problem could arise from the corrections from one segment blurring into the region for the next segment, since much of the wavefront-error sensing occurs at the pupil edges in Roddier's examples. If the entire primary can be treated as a single pupil rather than discrete segments, this problem should be negligible, and is another justification for establishing sensing pupil planes where the detector pixel dimensions are large, as compared with the demagnified spacing between mirror segments. If the entire primary is treated together, an identical tilt error in two segments might become invisible to the Roddier sensing system at positions representing the boundary between the two segments, but the tilt error will still be recognized as such for the larger double-segment portion of the primary around the perimeter of the two.

The Roddier approach can have a very simple hardware implementation, using a single charge-coupled device (CCD) detector array on a calibrated translation stage and a sliding planar mirror to deflect the incident light to the sensing optics when required. Alternatively, a beam splitter and two CCD arrays can be used in the sensing system instead of the calibrated translation stage. The sliding mirror would remain in a stowed position during signal reception. This approach also assumes a calibrated object, which requires a table of stars.

IV. Control Approaches

There are several published methods for control of the actuators realigning the segments of the primary mirror for figure correction. These approaches tend to use state-space representations and differ primarily in the manner that the sensed information is manipulated to observe the state variables and subsequently change them with feedback to minimize rms wavefront error. Therefore, the implementation of a control algorithm depends largely on the sensing approach taken. Often the high-frequency errors, such as mechanical vibrations and atmospheric distortions, are corrected by local control loops, while the quasi-static figure errors due to thermal distortion and force loading are controlled by global loops.

Iwens, Benhabib, and Major present a system that uses several sensing systems to control line-of-sight and wavefront errors [8]. The actuators for this system are an array of stacked piezoelectric crystals. A digital computing system is used for handling the control. The system is intended primarily to compensate for vibration errors in a spaceborne system; however, a low-pass filtering of wavefront sensing signals could be used for quasi-static correction only, assuming that the high-frequency vibration error has zero mean.

The PSR control system, shown in Fig. 4, uses a hybrid approach of high-bandwidth local vibrational correction and quasi-static global figure control [9]. Edge sensing is used to measure relative displacement between adjacent panels to detect quasi-static figure errors. High-frequency vibrations are detected by accelerometers on the back side of the mirror segments. A triangular orientation of piston actuators is used to control piston and tilt in each panel.

Downie and Goodman present a method of designing an optimized control system for a segmented mirror that corrects both atmospheric and quasi-static figure errors [10]. The design takes into account the sensitivity of wavefront correction to the motion of each actuator. Assuming a zero-mean distortion due to atmospheric fluctuations, this design approach could be used to optimize control of only quasi-static errors.

V. Conclusion

A preliminary investigation of active mirror-segment control for a deep-space optical receiver telescope has been presented. Since this telescope requires only limited imaging capability, the primary purpose of active optics is the optimum concentration of signal light power inside a detector radius. Since diffraction-limited resolution is not required, there is less justification of expensive components, such as high-quality primary mirror surfaces. High-bandwidth compensation for wavefront distortion due to atmospheric fluctuation and structure vibration is also less justifiable. Low-bandwidth compensation for thermal expansion and force-load figure distortion is economically feasible, providing that sensing of wavefront errors for these distortions can be performed easily.

Three methods have been presented for sensing wavefront errors due to quasi-static distortions. Of these, the Roddier system is probably the least expensive to implement in hardware, but this system was designed to operate with a continuous-membrane mirror. Adaptation for a segmented mirror system is unlikely to be straightforward. The Hartmann method is probably intermediate in hardware expense, with the principal costs due to the deflection optics used to subdivide the primary-mirror aperture and a segmented CCD array sensor with enough resolution in each of the 60 subaperture-sensing regions. The PSR edge-sensing system is probably the most expensive, but possibly the easiest to manufacture because it is already in development for a similar large segmented-mirror system and much of the design has already been completed.

The control algorithm chosen must be compatible with the sensing and actuator system used, and therefore cannot be planned until a sensing approach has been chosen. Two example control systems and a method for optimization of the control system, once sensor and actuator parameters are known, have been identified in the literature.

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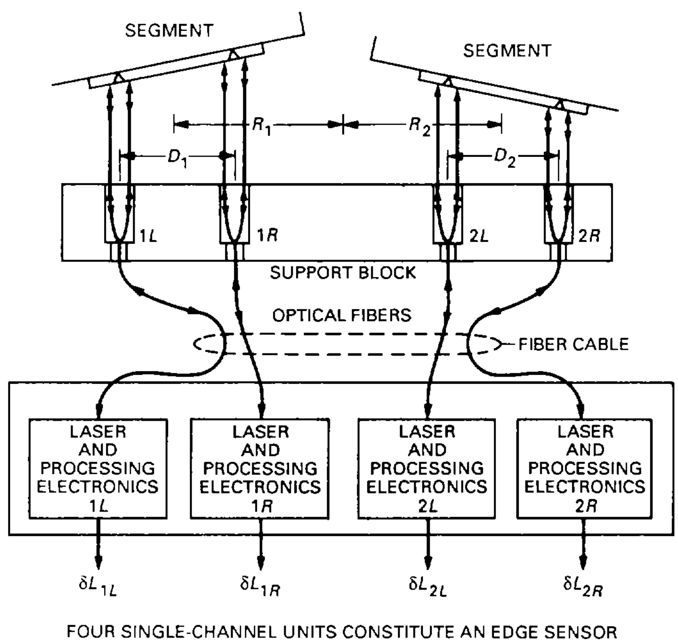

Fig. 1. Back-surface edge sensing in the Precision Segmented Reflector system.

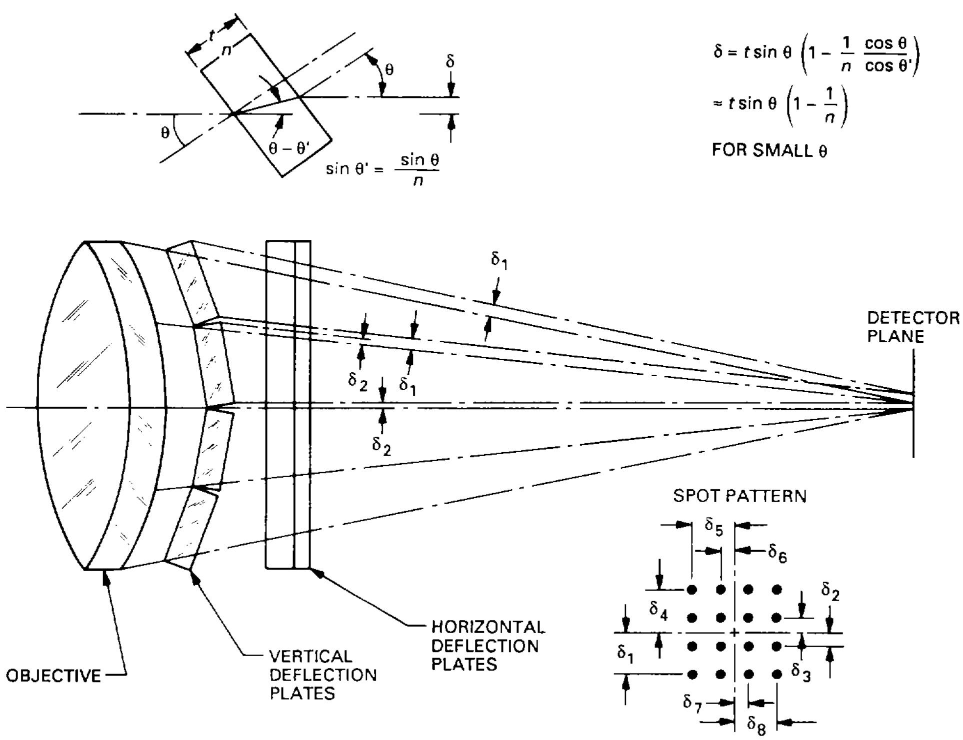

Fig. 2. The Hartmann wavefront sensing technique.

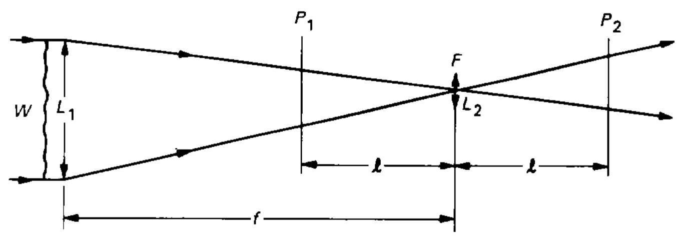

Fig. 3. The Roddier wavefront sensing technique.

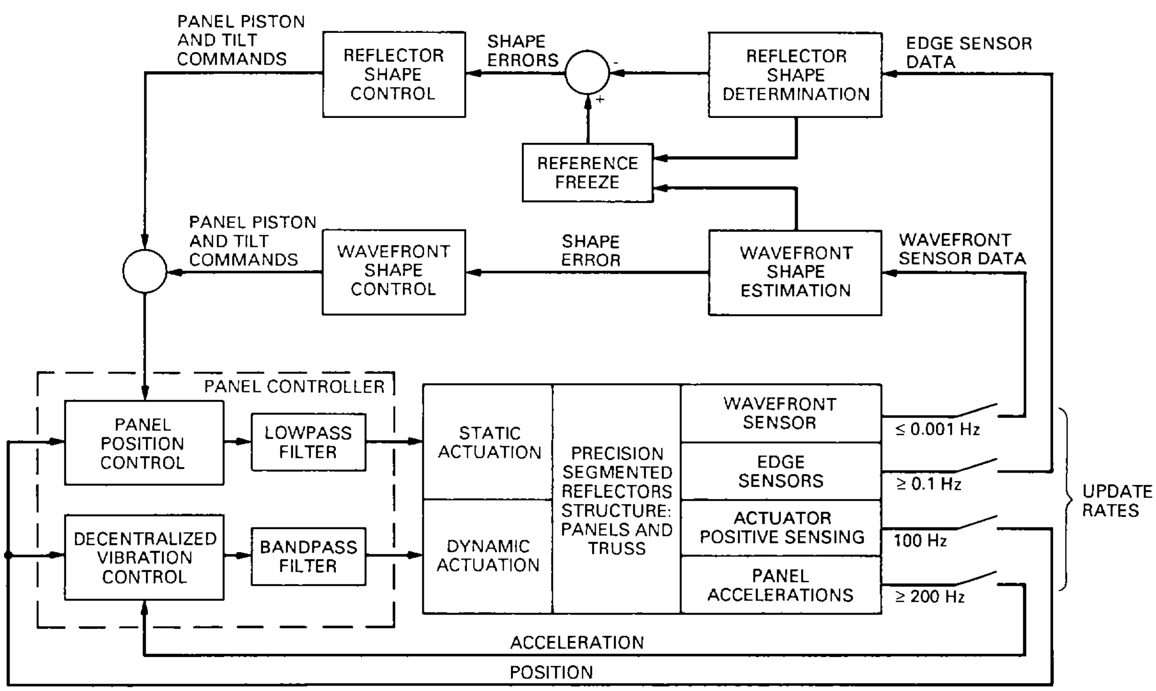

Fig. 4. The Precision Segmented Reflector control system.